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Magneto-Elastic Behaviour of Steels for Naval Applications

I.M. Robertson

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Abstract

Naval vessels become magnetized during construction and service due to the combined action of the earth's magnetic field and mechanical stress. The magnetic signature must be kept to a minimum to reduce vulnerability to magnetic mines and magnetic anomaly detection. In this work the magneto-elastic behaviours of various steels used in naval construction are compared, with particular emphasis on submarine hull steels. Magnetic field strengths of the order of the earth's field, and stresses up to 200 MPa are examined. All the steels examined have similar qualitative behaviour, but the quantitative behaviour is quite different. Mild steel is easily magnetized, HSLA80 is more difficult, and the HY steels (HY80 and HY100) more difficult again. The initial permeability of the steel is a good guide to the degree of magnetization caused by either stress or field cycling.

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Contents

Magneto-Elastic Behaviour of Steels for Naval Applications

1. Introduction

The magneto-elastic behaviour of naval steels has significance because service stresses and the earth's magnetic field combine to cause an increase in the magnetic signature of the ship or submarine. The increase in signature can be much larger than that due to the earth's field alone. Magnetic signature is important for two main reasons:

(i) magnetic actuators in mines;
(ii) magnetic anomaly detection of submarines by maritime aircraft.

In this work the magnetization induced in a variety of steels due to stress or field cycling has been measured. The steels examined were:

- Mild Steel
- HSLA80
- HY80
- HY100
- BIS 812 EMA (untempered)

The mild steel and untempered BIS 812 EMA were included for comparison purposes and to broaden the range of magnetic properties. Mild steel is magnetically soft, and untempered BIS 812 EMA magnetically hard compared with the other steels.

BIS 812 EMA is the steel selected for the pressure hull of Australia's Type 471 submarine. The magneto-elastic behaviour of this steel in its normal quenched and tempered condition has been compared with quenched and tempered QT28 in a parallel investigation (Robertson, 1990a). BIS 812 EMA is a microalloy-augmented, martensitic steel, quenched and tempered to a minimum yield strength of 690 MPa. In the as-quenched (untempered) condition the strength is of course much higher.

HY80 and HY100 are high strength, weldable martensitic steels which have been used for many years in naval construction. HY80 and its equivalents are the standard steels for western world submarine pressure hulls. The steels are more highly alloyed than BIS 812 EMA, but receive similar heat treatment. They are quenched and tempered to achieve minimum yield strengths of 560 MPa and 690 MPa respectively.

HSLA80 is a more recent development. The steel contains a significant concentration of copper, which contributes to its strength by means of precipitation hardening. Potential construction cost savings accrue from the use of HSLA80 because of reduced welding preheat requirements compared with HY80 for example. HSLA80 receives thermomechanical processing during rolling operations, rather than a quench and temper (which must be carried out after plate has cooled from the rolling operations).

Information available from the literature on the effects of stress and field fluctuations on the magnetization of steels is reviewed in a separate document (Robertson, 1990b). The fundamental effect is that the fluctuations cause the magnetization to increase or decrease towards the anhysteretic (equilibrium) level. The rate of approach to the anhysteretic is determined by the magnitude of the stress or field fluctuation relative to the coercivity of the steel. Coercivity generally increases as the strength of the steel increases, so higher strength steels show smaller change of magnetization for a given stress or field fluctuation. The magnetostriction also plays a role. The chemical composition of the steel is the most important factor in controlling the magnetostriction.

2. *Experimental Procedure*

2.1 *Apparatus*

The equipment necessary for measurement of the effects of stress on the magnetization of steel was constructed at MRL, as other laboratories in Australia are not equipped to carry out such measurements. The construction, calibration and operation of this equipment is described elsewhere (Robertson and Vincent, 1990). Because primary interest is in the submarine pressure hull application, the apparatus is designed to measure the effects of compressive stress cycles on the magnetization of the specimens. Minor modifications would allow the investigation of the effects of tensile stress.

The apparatus consists of five main components as follows:

(i) A Riehle screw-driven tension/compression testing machine for applying compressive loads to the test specimens.

(ii) Electronic circuits for applying known H fields and measuring the resultant B fields[1] induced in the specimens by means of coils wound on the specimens. The B field is measured by integration of the emf induced in the

[1] The B and H fields are related by the equation $B = \mu H$ where B is the magnetic induction, H the magnetic field intensity and μ the permeability.

B coil as a result of changes in the current supplied to the H coil. Separate provision is made for demagnetizing the specimens using the H coils.

(iii) A magnetic circuit consisting of two identical test specimens connected by two soft iron yokes as shown in Figure 1. The B and H coils are wound on formers, allowing different test specimens to be inserted. The specimens are preferably long and thin to avoid demagnetization effects, but are also preferably short and squat to avoid buckling under compressive load. The specimen dimensions selected represent a compromise between these requirements. The specimens are magnetically insulated from the testing machine platens with sheets of non-magnetic stainless steel.

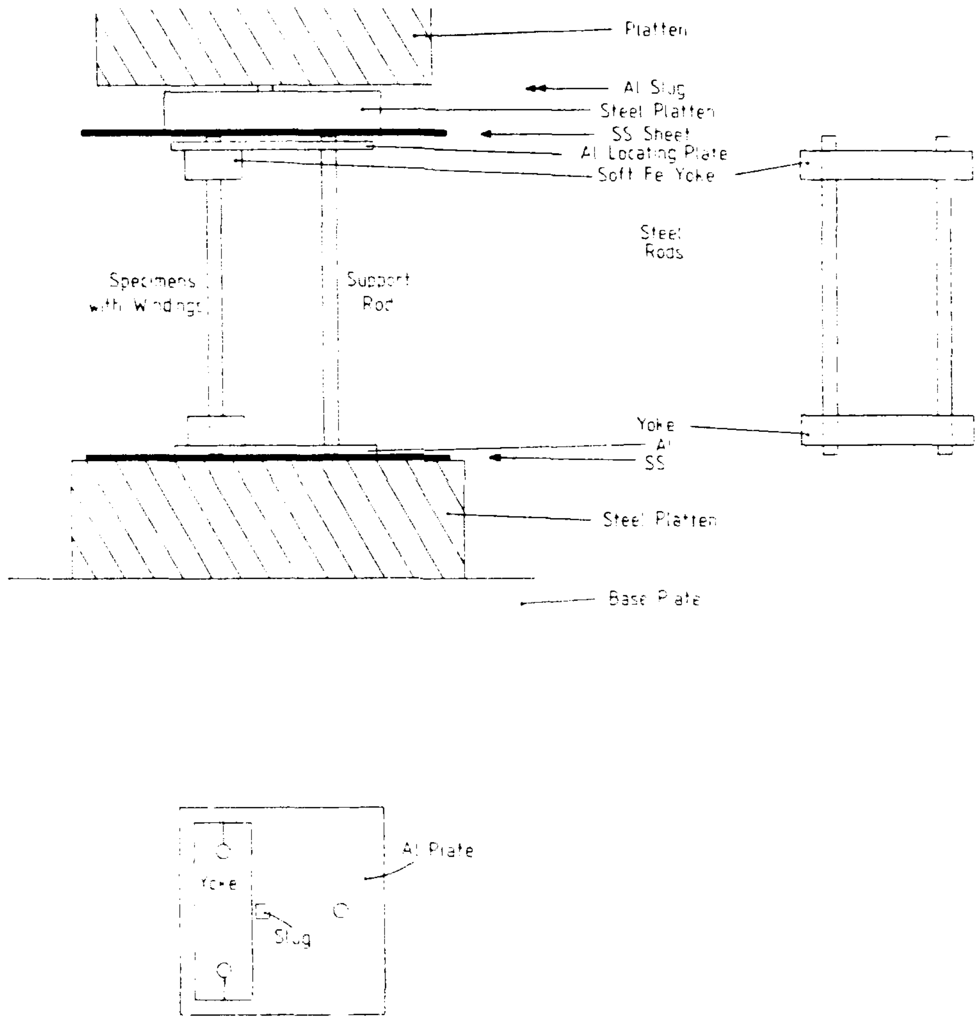


Figure 1: Elevation, end elevation, and plan view of the magnetic circuit and arrangement for applying compressive stress to test specimens in use at MRL.

(iv) A third steel rod of the same dimensions as the magnetic specimens, arranged as shown in Figure 1, to increase the mechanical stability under compressive load. This rod is not part of the magnetic circuit. Holes drilled in two aluminium plates locate the three steel rods. A small aluminium slug is placed on the loading machine platen, at the centroid of the triangle formed by the three rods, to eliminate any misorientation of the platens and ensure that each steel rod carries the same load.

(v) An X-Y recorder for plotting changes in B against stress or H field. Digital voltmeters were often used in place of the X-Y recorder.

This arrangement eliminates the sliding magnetic contacts necessary in some experimental arrangements due to contraction under stress (e.g. Craik and Wood, 1970). The design is based on the Burrows permeameter (Spooner, 1927) and is similar to the arrangement used by Lliboutry (1951).

2.2 *Materials and Sample Preparation*

The test specimens were cylindrical in form with dimensions 10.25 mm diameter by 210 mm long. The preparation procedure in most cases was as follows:

(i) cut blanks from as-received plate;
(ii) turn to slightly oversize diameter;
(iii) stress relieve at 550°C for one hour;
(iv) centreless grind to final diameter.

Exceptions to this were the mild steel, which was machined from bar stock directly to final size without stress relief, and the untempered BIS 812 EMA, which was water quenched after fifteen minutes in a salt bath at 915°C and not stress relieved (or tempered).

The sources of the steel plates used in the investigation and the orientation and location from which the specimens were taken are shown in Table 1. Chemical analysis results are listed in Table 2. Vickers hardness profiles through the plate thickness are shown in Figure 2. The stress relieving treatments did not affect the hardness.

2.3 *Magnetic Processes Investigated*

The magnetic processes investigated consisted of varying the stress at constant field and varying the field at constant stress. In all cases the stress was uni-axial compression, applied parallel to the H field. The B field was measured parallel to the H field along the axis of the specimen. The processes were as follows:

(i) $DH(\sigma\bar{\sigma})^n$ process, consisting of a demagnetization treatment followed by application of magnetic field H, and n cycles of application and removal of compressive stress σ.

(ii) $D\sigma h_{n}$ process, consisting of demagnetization, application of stress, followed by n cycles of a fully reversed H field (cycling between +h and -h). (See the Appendix for a more complete description of the notation).

Table 1: Sources of Steel Specimens

Steel	HSLA80	HY80	HY100	BIS 812 EMA
Source of plate	BHP	Bunge	Bunge	Bunge
Plate thickness (mm)	25	32	25	35
Orientation of specimen to RD	Parallel	Parallel	Perpendicular	Parallel
Location of specimen through the thickness of the plate	Mid-thickness	Mid-thickness	Mid-thickness	Half way between surface and midplane

Table 2: Chemical Composition

	HSLA80	HY80	HY100	BIS 812 EMA
C	0.06	0.12	0.15	0.14
Si	0.29	0.17	0.28	0.25
Mn	1.41	0.16	0.27	0.91
P	0.011	0.019	0.013	0.010
S	0.002	0.011	0.002	0.002
Ni	0.80	2.85	3.02	1.26
Cr	0.01	1.32	1.49	0.45
Mo	0.01	0.50	0.50	0.38
Cu	0.98	0.03	0.03	0.19
Ti	0.01	< 0.01	< 0.01	0.01
Nb	0.02	0.01	0.01	0.01
V	< 0.01	< 0.01	< 0.01	0.02
Al	0.027	0.057	0.040	0.095
B	0.0005	< 0.0005	< 0.0005	0.0044

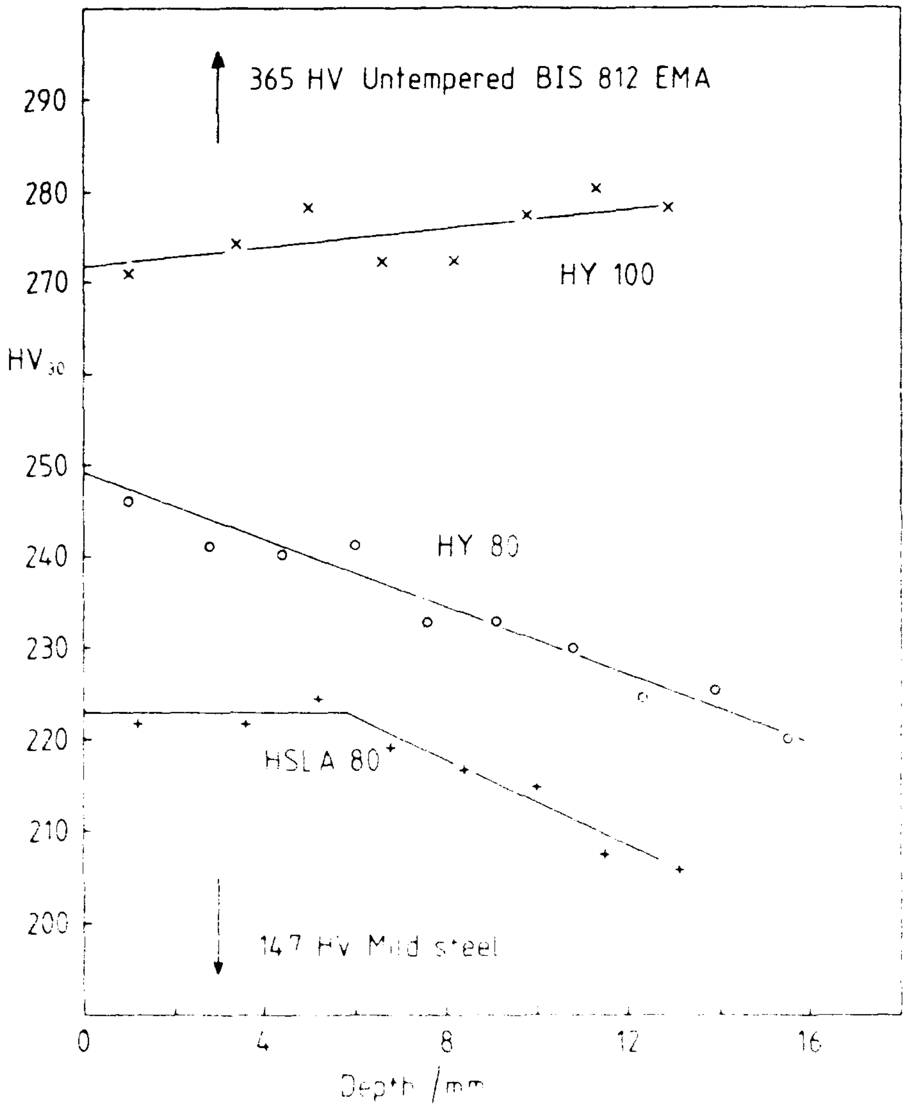


Figure 2: Vickers hardness profiles through the thickness of plates of HY100, HY80 and HSLA80 steels. The hardnesses of the mild steel and untempered BIS 812 EMA specimens are also shown.

The stress level was -200 MPa for the $DH(\sigma\bar{\sigma})^n$ process, and ranged from 0 to -200 MPa for the $D\sigma\hat{h}$ process. The H field amplitude selected depended on the magnetic hardness of the steel, and ranged up to 200 A/m (although normal induction curves were measured up to 1000 A/m). The earth's magnetic field is typically 40 A/m.

Some data was obtained for the $D\sigma(h\bar{h})^n$ process in which the H field varies between zero and h rather than being reversed as in the $D\sigma\hat{h}$ process.

3. Results

3.1 Normal Induction Curves

The normal induction curves measured for the various steels are shown in Figure 3. As expected from the hardness levels (Fig. 2), the approximate order of increasing magnetic hardness is MS, HSLA80, HY80, HY100 and untempered BIS 812 EMA. It should be noted that the MRL apparatus does not meet the requirements of the relevant ASTM standards (ASTM A431, A596, A773) because of the design constraints to allow the application of stress. Even for the permeameters considered by ASTM A773 it is well known that test results obtained with one type of permeameter may not compare closely with those obtained on the same specimen from another type of permeameter. Therefore Figure 3 should be regarded as a comparison of the steels rather than an absolute measurement of the normal induction curves.

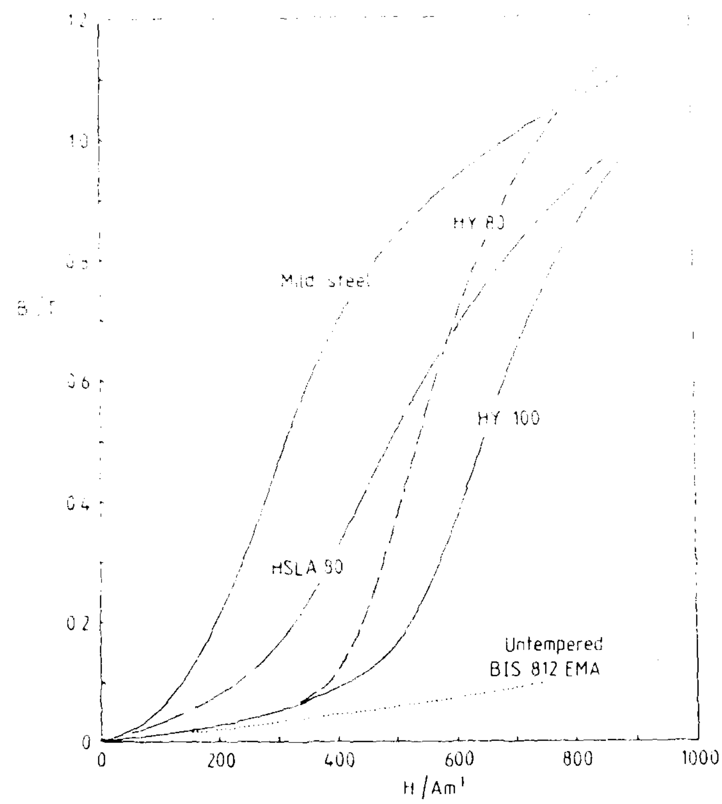


Figure 3: Normal induction curves measured at MRL for the five steels examined.

3.2 $DH(\sigma\bar{\sigma})^n$ Process

Of the two processes investigated, $DH(\sigma\bar{\sigma})^n$ causes the larger increase in magnetization. The $D\sigma h_{\sim}$ process to be described in Section 3.3 causes less magnetization because the stress is applied in the absence of a magnetic field.

3.2.1 *H Field of 50 A/m*

Figure 4 shows the schematic response of the steels to the $DH(\sigma\bar{\sigma})^n$ process. Most of the magnetization change occurs in the first cycle of stress application and removal. The magnetization then follows an almost closed loop. Actual test results for HY100 with H = 50 A/m and σ = -200 MPa (Fig. 5) show that the "closed" loop actually moves slowly upwards for the first few cycles before stabilizing. Because of magnetostriction, application of stress helps to move magnetic domain boundaries past obstacles which the H field alone cannot overcome. The magnetization therefore increases.

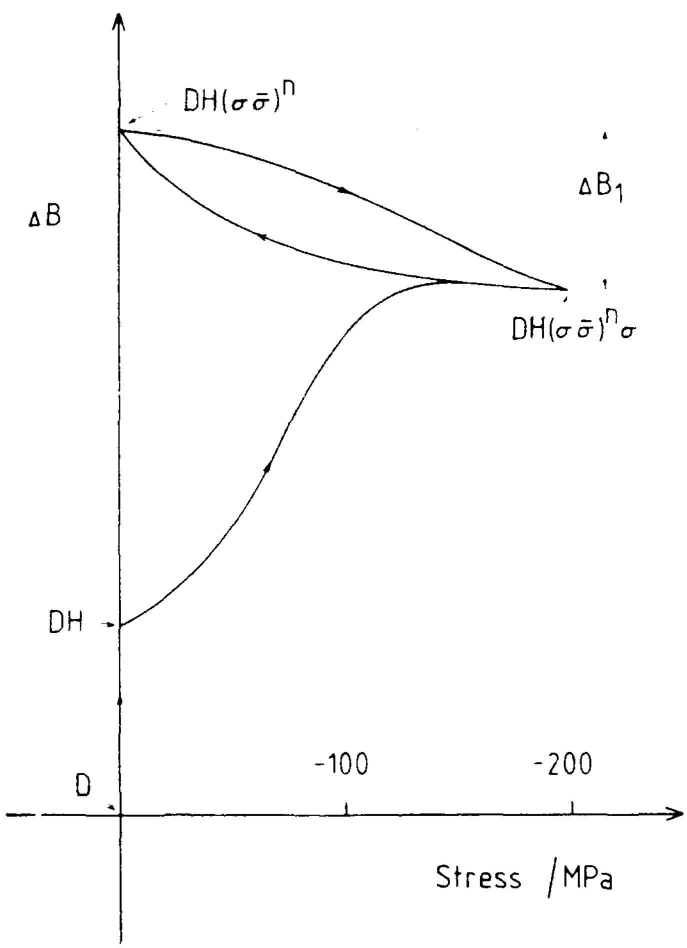


Figure 4: Schematic diagram showing the increase in magnetization of steel subjected to the $DH(\sigma\bar{\sigma})^n$ process.

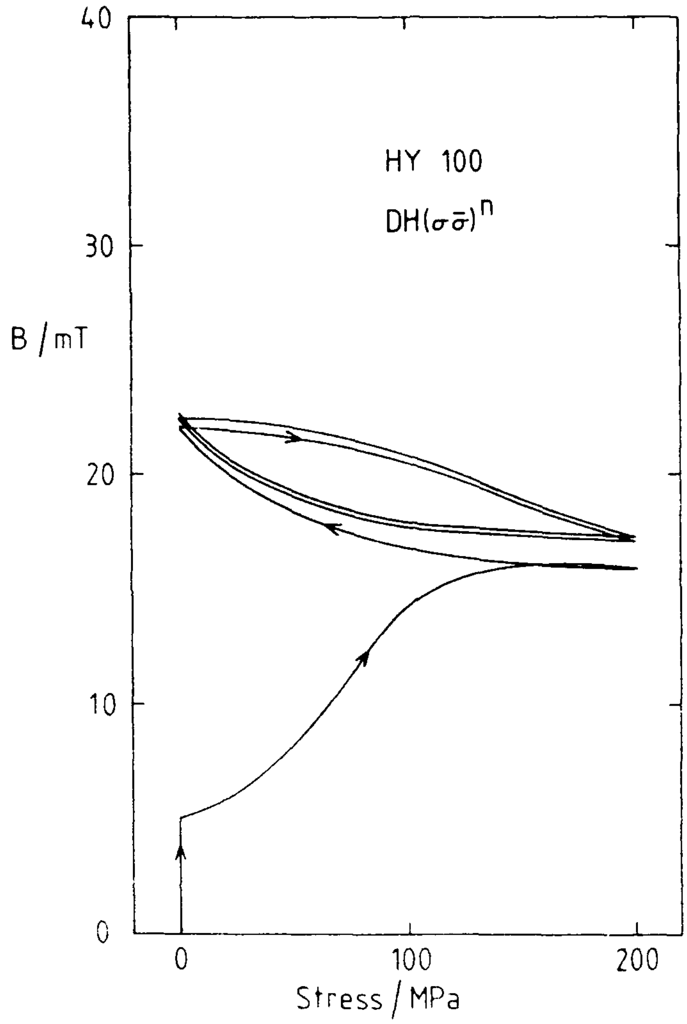


Figure 5: Response of HY100 steel to the DH($\sigma\bar{\sigma}$)^n process with H = 50 A/m and σ = -200 MPa.

The behaviour of the steels during the first stress cycle (again for H = 50 A/m and σ = -200 MPa) are compared in Figure 6. On the basis of these curves the steels can be classified into three broad groups:

(i) The magnetically soft steels MS and HSLA80 exhibit very large increases in magnetization due to the stress cycle.

(ii) The quenched and tempered steels HY80 and HY100 show an intermediate response.

(iii) The magnetically hard, untempered BIS 812 EMA manifests only a small response to stress cycling (less than that caused by the H field itself).

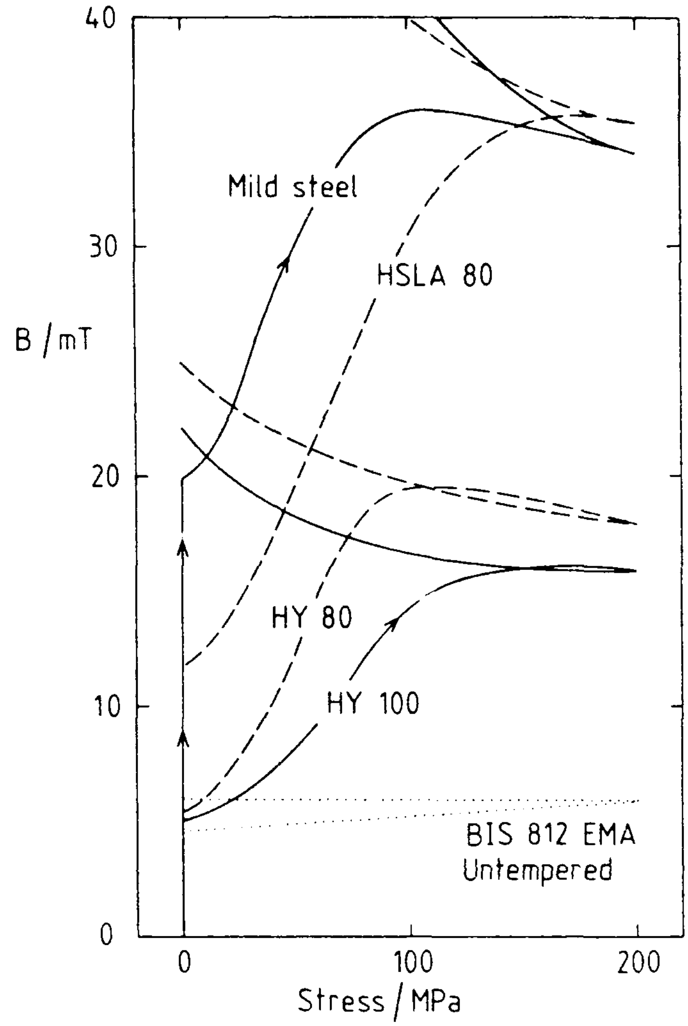


Figure 6: Response of various steels to the first cycle of the $DH(\sigma\bar{\sigma})^n$ process with $H = 50$ A/m and $\sigma = -200$ MPa.

The behaviour of the steels during subsequent stress cycles allows a similar grouping:

(i) The "closed" loops of MS and HSLA80 move upwards by significant amounts, and continue to move until about 8–10 cycles have been completed. The difference in B value between the tips of the stable loop is large (30 mT for MS, 19 mT for HSLA80).

(ii) The "closed" loops of HY80 and HY100 move upward by a small amount and stabilize after about three cycles. The difference in B value between the tips of the stable loop is much smaller than for the magnetically soft steels (6 mT for both HY80 and HY100).

(iii) Untempered BIS 812 EMA is essentially stable after the first cycle. The difference in B value between the tips of the stable loop is very small (0.2 mT).

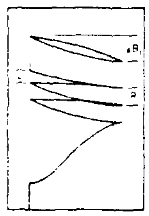
Typical data for the upward creep of the "closed" loops for H = 50 A/m and σ = -200 MPa are listed in Table 3. The B increments for the left and right hand tips of the loop with each stress cycle are listed. The increments decay in an approximately logarithmic fashion. (See also Schneider and Semcken, 1981).

Table 3: *Creeping of Hysteresis Loops in the $DH(\sigma\bar{\sigma})^n$ Process (Typical values for H = 50 A/m and σ = -200 MPa)*

	Steel	MS		HSLA80		HY80		HY100		BIS 812 EMA (Untempered)	
	Point on Loop	L*	R*	L	R	L	R	L	R	L	R
n											
1	ΔB/mT	3.7	4.6	3.2	3.8	0.4	0.9	0.4	1.1	0	0
2		1.9	1.6	2.0	1.2	0.2	0.5	0.2	0.3		
3		1.5	1.2	1.5	1.0	0.1	0.2	0.1	0.1		
4		0.9	0.9	0.8	0.8						
5		0.7	0.7	0.6	0.6						
6				0.3	0.3						
6	B Difference between Tips of Stable Loop	30		19		6		6		0.2	

* $L = DH(\sigma\bar{\sigma})^{n-1} - DH(\sigma\bar{\sigma})^{n}$

$R = DH(\sigma\bar{\sigma})^{n}\sigma - DH(\sigma\bar{\sigma})^{n-1}\sigma$



3.2.2 *Other H Values in the $DH(\sigma\bar{\sigma})^n$ Process*

Results for HY100 with σ = -200 MPa and H values in the range -100 to +150 A/m are summarized in Figure 7. The results for the other steels are similar in form, although as noted above the actual magnetization levels differ markedly. Five curves are shown, indicating the change in magnetization on passing from one condition to another:

(i) DH - D is the normal induction curve (the difference between the DH condition and the demagnetized condition D).

(ii) $DH\sigma$ - DH represents the change in magnetization due to the application of stress σ at constant H field. Curves are for σ = -100 MPa and -200 MPa.

(iii) $DH\sigma\bar{\sigma}$ - DH represents the change due to application and removal of stress (-200 MPa) at constant H.

(iv) $DH(\sigma\bar{\sigma})^{n+1} - DH(\sigma\bar{\sigma})^n \sigma$ shows the change during removal of the stress after n cycles when the magnetization is following a stable loop (last row in Table 3). The magnetization difference is designated ΔB_1 in Figure 4.

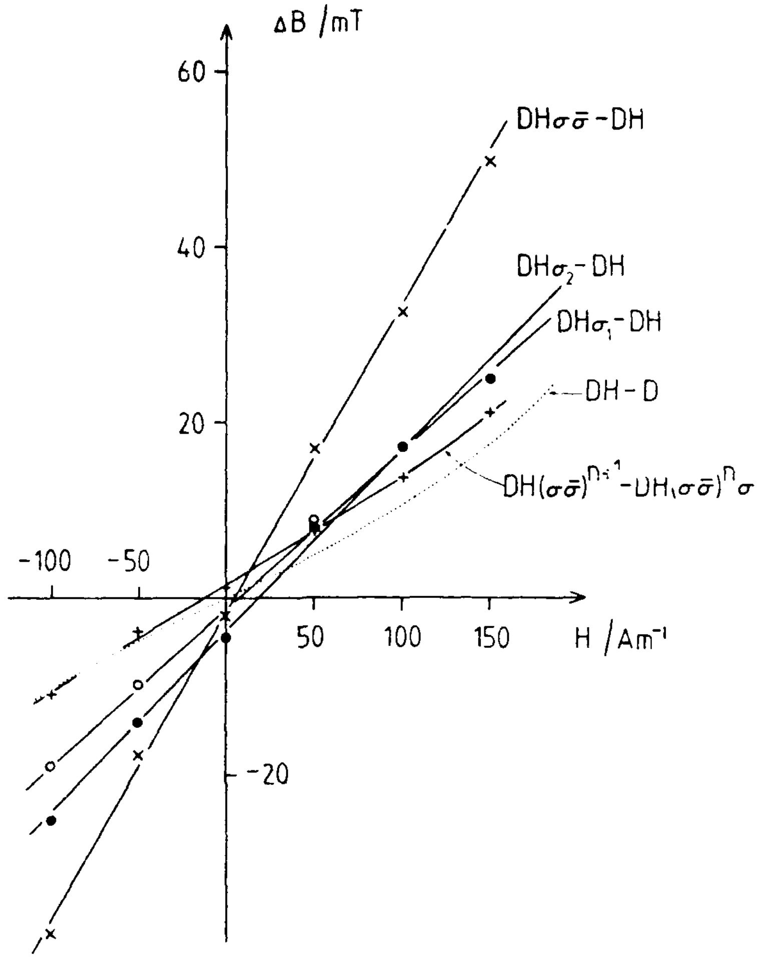


Figure 7: Magnetization changes on passing from one magnetic state to another for HY100 steel undergoing the $DH(\sigma\bar{\sigma})^n$ process with σ = -200 MPa. See text for details. For the DHσ-DH curves, σ_1 represents a stress of -100 MPa, and σ_2 a stress of -200 MPa.

Allowing for small zero offsets due to residual magnetization after "demagnetizing", in all cases the change in magnetization is proportional to the applied field H for field strengths of the order of the earth's field (there is some curvature for higher field strength). Provided we are interested only in such weak fields, the change in magnetization can be calculated from the expression

$$\Delta B = mH \tag{1}$$

where H is the field strength and m is the slope of the relevant curve in Figure 7.

Results for the other steels showed similar linear relationships. The slopes of the curves (m values) are listed in Table 4. Measurements carried out on other steels show that m increases non-linearly with increasing stress (Robertson, 1990a).

Table 4: Initial Slopes of ΔB - H Curves for the $DH(\sigma\bar{\sigma})^n$ Process with σ = -200 MPa

Steel	Initial Slope of the ΔB - H Curve Indicated /mT per Am^{-1}				
	DH-D (μ_Δ)	DHσ-DH (σ = - 100 MPa)	DHσ-DH (σ = - 200 MPa)	DH$\sigma\bar{\sigma}$-DH (σ = - 200 MPa)	ΔB_1 *
MS	0.37	~ 0.29	~ 0.27	0.86	0.60
HSLA80	0.22	~ 0.36	~ 0.48	0.78	0.38
HY80	0.100	~ 0.25	~ 0.19	0.33	0.12
HY100	0.098	0.18	0.21	0.35	0.12
BIS 812 EMA (Untempered)	0.090	0.011	0.024	0.028	0.004

* ΔB_1 refers to the stable loop in Figure 4.

3.3 $D\sigma h_{\sim}$ and $D\sigma(h\bar{h})^n$ Processes

Schematic diagrams of the field cycling processes are shown in Figure 8. As in the case of the $DH(\sigma\bar{\sigma})^n$ process, an almost stable hysteresis loop is followed during field cycling once the first cycle is complete. Because the average H field is zero in the $D\sigma h_{\sim}$ process, the stable hysteresis loop is centred about the B-H origin (simply because of symmetry).

Results for HY100 undergoing these processes at a stress level of - 200 MPa and field cycle amplitudes ranging from - 25 A/M to + 100 A/m are shown in Figure 9. For h values of the order of the earth's magnetic field (up to 40 A/m), the change in magnetization on passing from one state to another is approximately proportional to the field amplitude h. Some curvature becomes noticeable at the higher field strengths, especially for the $D\sigma h\bar{h}$ - $D\sigma$ curve, and to a lesser extent for the $D\sigma h$ - $D\sigma$ curve.

The behaviour of HY100 at σ = - 200 MPa described above is typical of other steels and other stress levels. In all cases the ΔB - h curves are linear at low field strengths, so once again

$$\Delta B = mh \tag{2}$$

where m is the slope of the relevant curve (as in Fig. 9) and h is the field amplitude. The m values for the steels investigated with stress levels ranging from zero to - 200 MPa in the $D\sigma h_{\sim}$ and $D\sigma(h\bar{h})^n$ processes are listed in Table 5.

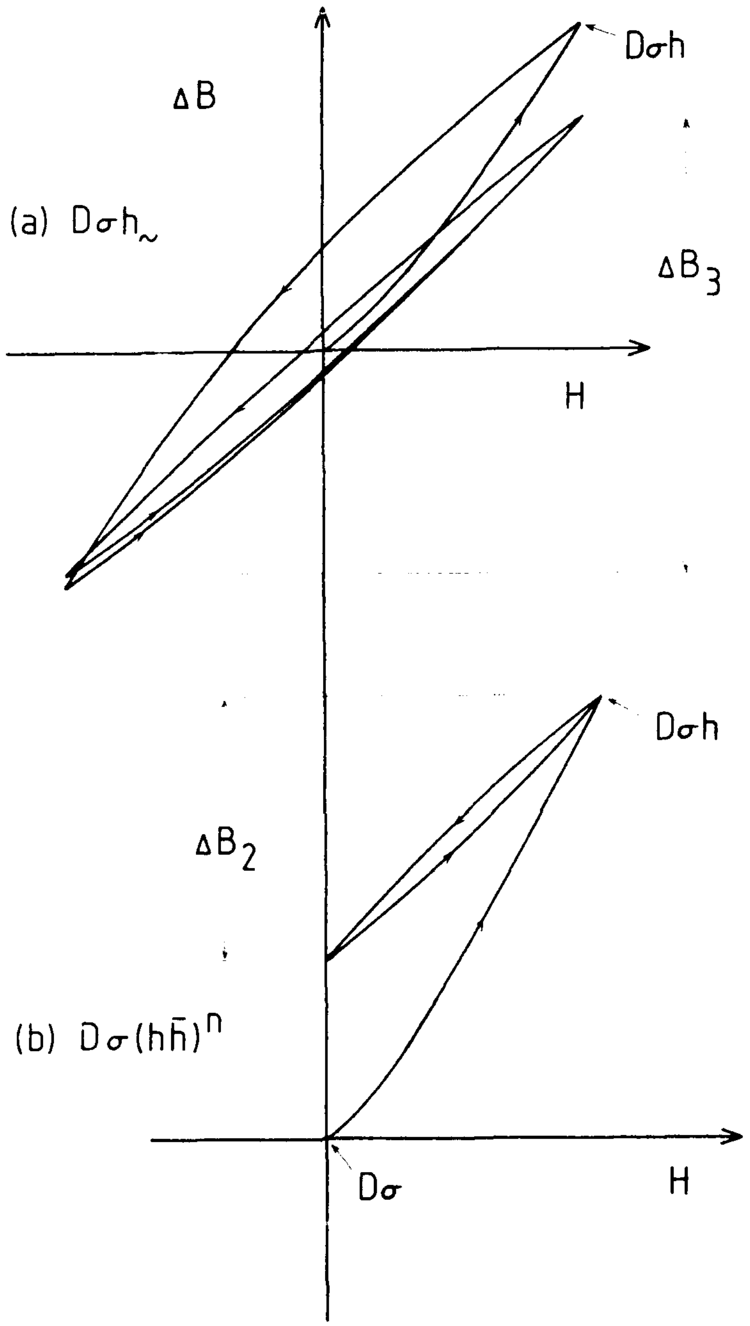


Figure 8: Schematic diagrams showing the increase in magnetization of steel subjected to the $D\sigma h_{\sim}$ and $D\sigma(h\bar{h})^n$ processes (up to the point $D\sigma h\bar{h}$ the processes are identical).

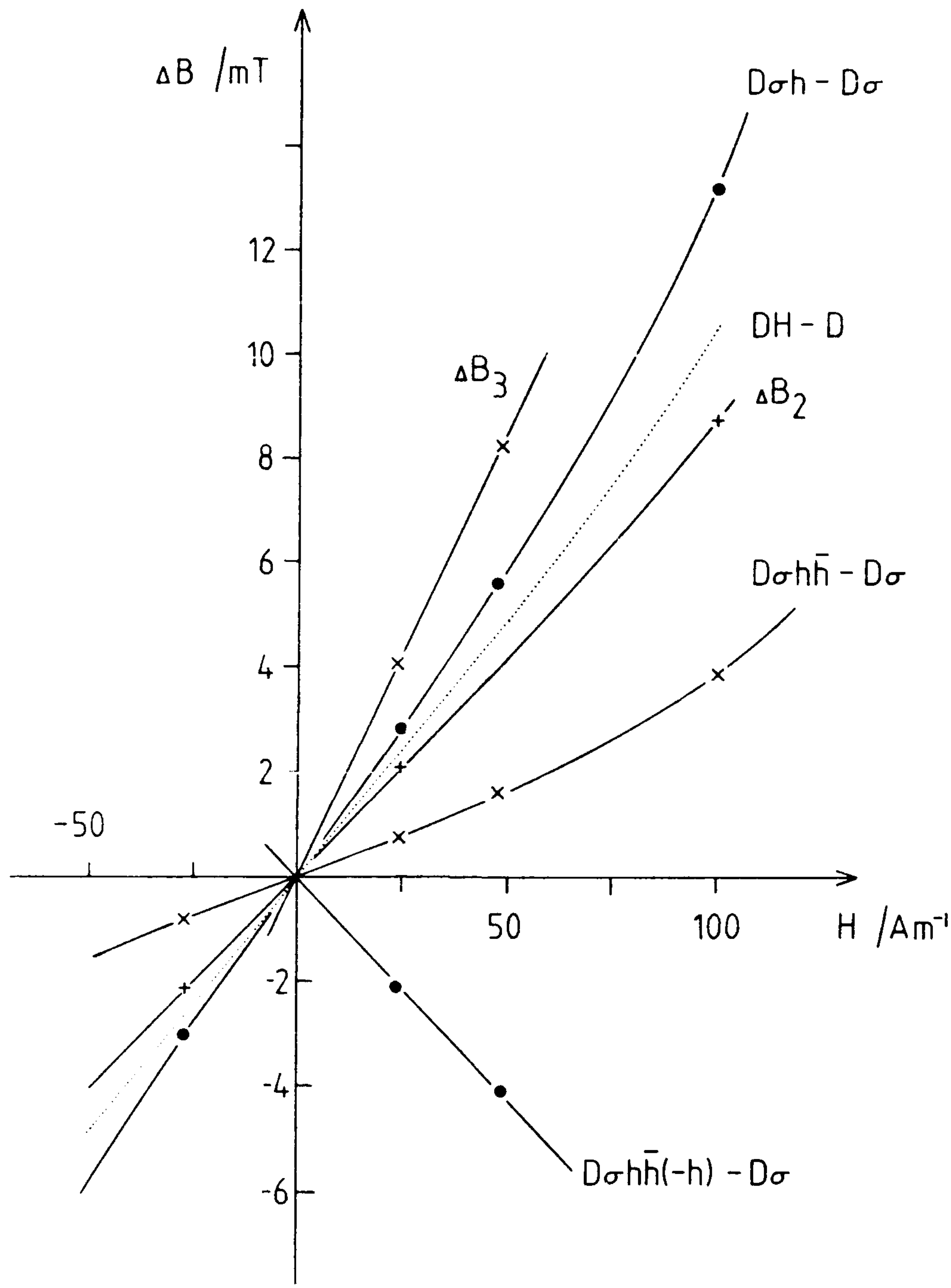


Figure 9: Magnetization changes on passing from one magnetic state to another for HY100 steel undergoing the $D\sigma \tilde{h}$ and $D\sigma(h\bar{h})^n$ processes with σ = - 200 MPa. The curves ΔB_2 and ΔB_3 refer to the stable loops shown in Figure 8.

Table 5: Initial Slopes of ΔB - h Curves for the $D\sigma(h\bar{h})^n$ and $D\sigma h_{\wedge}$ Processes

Steel	σ/MPa	Initial Slope of the ΔB - h Curve Indicated/mT per Am^{-1}				
		$D\sigma h$ - $D\sigma$	$D\sigma h\bar{h}$ - $D\sigma$	$D\sigma h\bar{h}(-h)$ - $D\sigma$	ΔB_2 *	ΔB_3 *
MS	0	0.34	0.03			0.74
	- 25	0.37	0.08			0.69
	- 50	0.37	0.09			0.63
	- 100	0.31	0.08			0.50
	- 150	0.27	0.07			0.43
	- 200	0.22	0.06			0.36
HSLA80	0	0.22	0.02	-	-	0.44
	- 50	0.24	0.06	-	-	0.40
	- 100	0.24	0.06	-	0.17	0.36
	- 150	0.21	0.05			0.32
	- 200	0.17	0.04			0.28
HY80	0	0.100	0.004			0.208
	- 50	0.137	0.035			0.199
	- 100	0.142	0.039			0.191
	- 150	0.118	0.026			0.180
	- 200	0.106	0.022			0.171
HY100	0	0.098	0.004	- 0.092	-	0.197
	- 50	0.112	0.017	-	-	0.193
	- 100	0.139	0.039	- 0.096	-	0.188
	- 150	0.124	0.026	-	-	0.180
	- 200	0.109	0.030	- 0.086	0.083	0.173
BIS 812 EMA (Untempered)	0	0.085	0.003			0.172
	- 50	0.086	0.004			0.168
	- 100	0.088	0.007			0.167
	- 150	0.089	0.008			0.168
	- 200	0.092	0.008			0.167

* ΔB_2 and ΔB_3 refer to the stable loops shown in Figure 8.

The steels fall into the same broad groupings as described in Section 3.2, although in the case of the $D\sigma h_{\wedge}$ and $D\sigma(h\bar{h})^n$ processes of interest here, HSLA80 is more of an intermediate case between MS and the HY steels, and untempered BIS 812 EMA is more similar to the HY steels (as in the normal induction curves of Fig. 3).

The data in Table 5 show a slight stress dependence. Increasing compressive stress reduces the ΔB_2 and ΔB_3 values of the stable hysteresis loops for all steels examined, but the effect diminishes as the hardness of the steel increases. For example, ΔB_3 for MS at - 200 MPa is half its value at zero stress, whereas for HY100 the corresponding reduction is only 13 percent (and is even less for untempered BIS 812 EMA). The m values for the other curves in Table 5 generally increase in magnitude with increasing compressive stress before decreasing again. In keeping with the coercivities of the steels, the stress levels at which the slopes peak are approximately as follows:

MS	- 40 MPa
HSLA80	- 75 MPa
HY80	- 90 MPa
HY100	- 110 MPa
BIS 812 EMA (untempered)	- 200 MPa

The ranking of the steels according to their sensitivity to stress is similar in the $DH(\sigma\bar{\sigma})^n$ process (Fig. 6). However in the latter case the distinction is less clear because the reversible and irreversible components of the magnetization increment act in opposite directions (see Robertson, 1990b), tending to cancel each other and mask the effect.

4. *Discussion*

It is usual to discuss the magnetization of steel and other materials as a result of stress or field cycling, in terms of its reversible and irreversible components. These relate to the induced and permanent components respectively of the magnetic signature of a ship. For the processes investigated here, the components ΔB_1, ΔB_2 and ΔB_3 (Figs 4 and 8) are the reversible components. The remainder of the magnetization increase in a particular process is the irreversible component (Atherton et al., 1988).

In general terms, the irreversible component arises from the steel moving towards its equilibrium magnetization (on the anhysteretic curve), given the magnitude of the H field applied to it. Because of hysteresis effects, some impetus in the form of a stress, field or temperature fluctuation is required to allow the steel to approach its equilibrium state.

The reversible component is described by the equilibrium thermodynamic relationship:

$$(\partial B/\partial \sigma)_H = (\partial \lambda/\partial H)_\sigma = \Lambda' \qquad (3)$$

where B is the induction (magnetization), H is the field, σ the stress and λ the magnetostriction (the strain accompanying magnetization). For the low field strengths of interest here, Λ' behaves in a similar fashion to the differential permeability

$$\mu' = (\partial B/\partial H)_\sigma \qquad (4)$$

which is a more accessible quantity than Λ' (Pravdin et al., 1979). Thus as far as reversible components are concerned, the effects of stress should be proportional to the effects of field:

$$(\partial B/\partial \sigma)_H = (\partial \lambda/\partial H)_\sigma \propto (\partial B/\partial H)_\sigma \qquad (5)$$

This prediction is borne out quite well by the ΔB_1 values recorded in this investigation. Figure 10 shows the m values from Tables 4 and 5 for ΔB_1 at $\sigma = 0$ and - 200 MPa. The one anomalous point is the ΔB_1 slope for untempered BIS 812 EMA. This can be explained by the large internal stresses due to the quenching treatment, which reduce the response to an externally applied stress (this specimen was not stress relieved in order to maintain high hardness). Figure 10 could be used to predict reversible magnetization increments for other steels from a measurement of the initial permeability (at low field strengths). As expected from Rayleigh's law, the ΔB_3 (zero stress) m value is twice the initial permeability (at zero stress). This relationship breaks down at higher field strengths because

$$\Delta B_3/h = m = 2\mu_o + 2vh \tag{6}$$

according to Rayleigh's law (v is a material constant).

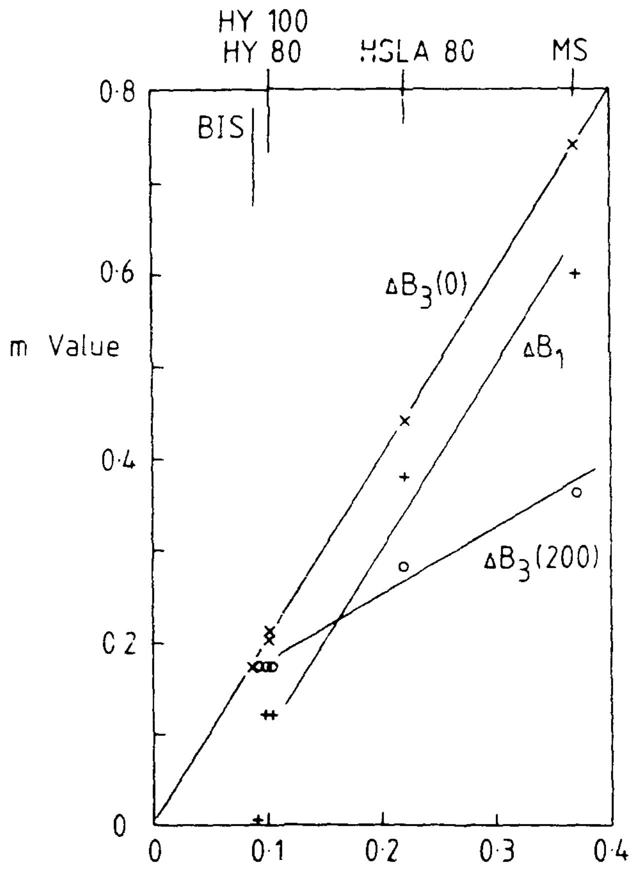


Figure 10: Correlation between initial permeability and initial slopes of ΔB-H curves (reversible components) for the $DH(\sigma\bar{\sigma})^n$ and $D\sigma h$ processes. ΔB_1 is as shown in Figure 4. ΔB_3 is as shown in Figure 8 (for stresses of 0 and - 200 MPa). Units are mT per A/m for both axes.

Turning to the irreversible component of magnetization change, the relevant data points are $DH(\sigma\bar{\sigma})^n$-DH and $D\sigma(h\bar{h})^n$-$D\sigma$ with n sufficiently large that a stable loop is being followed. The irreversible component is effectively zero for the $D\sigma\underset{\sim}{h}$ process (by symmetry). The irreversible magnetization change is expected to depend on the distance from the anhysteretic curve, and the size of the stress or field amplitude relative to the coercivity of the steel. Reference to the normal induction curves in Figure 3 indicates that at a given (small) H level, the distance to the anhysteretic curve should be greatest for HY80 and HY100, with mild steel and HSLA80 slightly less, and untempered BIS 812 EMA greatly less. The order of increasing coercivity of the steels is MS, HSLA80, HY80 and HY100 followed by untempered BIS 812 EMA (estimated from Fig. 3).

For BIS 812 EMA (untempered), both the distance to the anhysteretic and the stress/field amplitude relative to coercivity are small, so the irreversible magnetization change is small (there is also the internal stress discussed previously). In ranking the remaining steels, the two factors tend to act in opposite directions. It eventuates that the irreversible magnetization increments decrease as the coercivity increases (i.e. as the initial permeability decreases). The data in Tables 4 and 5 for $DH(\sigma\bar{\sigma})$ - DH and $D\sigma(h\bar{h})$ - $D\sigma$ could be used to predict irreversible magnetization increments for other steels as for the reversible increments discussed above.

5. *Conclusion*

All of the steels examined exhibit a similar type of response to the $DH(\sigma\bar{\sigma})^n$ and $D\sigma\underset{\sim}{h}$ magnetic processes, for stress and field fluctuation respectively. The difference between the steels is the magnitude of the response. Mild steel is the most easily magnetized, followed by HSLA80. The HY steels (HY80 and HY100) form an intermediate group, and untempered BIS 812 EMA is the most resistant to magnetization. The initial permeability is a good guide to the degree of magnetization of the steels in either the stress or field cycling processes.

Although HSLA80 and HY80 have the same nominal yield strength, the magnetic behaviour of HY80 more closely resembles the higher strength HY100. The thermo-mechanically processed, precipitation hardened HSLA80 is much more easily magnetized. HY80 and HY100 are very similar in chemical composition and in heat treatment (i.e. microstructure). It appears that this is more important than the strength level.

Ships constructed from HSLA80 can be expected to develop magnetic signature more quickly than an equivalent vessel constructed from HY80 or HY100. However, HSLA80 would be an improvement on mild steel as far as magnetic signature is concerned.

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Appendix

Notation for Magnetic Processes

The notation used to identify different magnetic processes in this report is based on conventional usage. The symbols used are as follows:

D	represents a demagnetizing treatment.
H	represents application of a magnetic field.
h	also represents application of a magnetic field but usually of smaller magnitude than H (see below).
σ	represents application of stress.
-	(over a symbol) represents removal of the field or stress.
$\sim$	(as a subscript) represents an oscillating field or stress.
n	(as a superscript) represents n repetitions of a process.

There is essentially no difference in the meaning of the symbols H and h, except that H usually means a constant (biasing) field and h a changing field of smaller magnitude superimposed on the biasing field.

The order of the symbols represents the order in which the steps of the magnetic process are carried out. For example, the $H\sigma\bar{\sigma}$ process involves application of field H followed by application of stress σ and then removal of the stress. The $DHh_{\sim}$ process involves demagnetization and application of a biasing field H followed by application of an additional oscillating field h (the total field varies between H - h and H - h).

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ABSTRACT

Naval vessels become magnetized during construction and service due to the combined action of the earth's magnetic field and mechanical stress. The magnetic signature must be kept to a minimum to reduce vulnerability to magnetic mines and magnetic anomaly detection. In this work the magneto-elastic behaviours of various steels used in naval construction are compared, with particular emphasis on submarine hull steels. Magnetic field strengths of the order of the earth's field, and stresses up to 200 MPa are examined. All the steels examined have similar qualitative behaviour, but the quantitative behaviour is quite different. Mild steel is easily magnetized, HSLA80 is more difficult, and the HY steels (HY80 and HY100) more difficult again. The initial permeability of the steel is a good guide to the degree of magnetization caused by either stress or field cycling.